

Relativistic Quantum Clock Fields and Compton-Phase Correlations

A Covariant Scalar-Field Description of Horizon-Scale Phase Structure

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Abstract

We propose a covariant effective field theory in which the Compton phase evolution of massive quantum systems is promoted to a dynamical scalar field $\phi(x)$. The field propagates as a massless scalar degree of freedom in flat spacetime and couples covariantly to electromagnetism and curvature through operators suppressed by the Compton frequency scale. In squeezed vacuum states naturally produced in pair-creation processes, the two-point correlation function of the clock field develops a long-range infrared component that yields distance-independent phase correlations between spatially separated systems. These correlations provide a physically motivated mechanism capable of mediating quantum phase correlations without violating relativistic causality. The framework predicts acceleration-dependent modulation of phase correlations and a relic cosmological clock-noise background potentially detectable with atomic-clock networks and pulsar-timing arrays.

1. Introduction

Modern unification in physics has repeatedly emerged through recognition of deeper dynamical structures linking apparently distinct observables:

- electromagnetism unified electric and magnetic fields,
- general relativity unified space and time,
- quantum theory unified energy and frequency.

A further structural relation appears between **mass and proper-time phase evolution** through the Compton frequency

$$m\tau_c = \frac{\hbar}{c^2}$$

This relation suggests that proper-time phase evolution may itself admit a field-theoretic description.

Motivated by this observation, we introduce a scalar **clock field**

$$\phi(x)$$

representing spacetime modulation of Compton phase evolution and construct its lowest-order covariant effective field theory.

The resulting framework predicts long-range phase correlations in squeezed vacuum states while preserving Lorentz invariance and micro-causality.

2. Compton Phase as a Scalar Field

For a massive particle evolving along a worldline with proper time τ

$$\psi \propto e^{-i\omega_c \tau}$$

We promote this phase evolution to a spacetime scalar field satisfying

$$u^\mu \nabla_\mu \phi = \omega_c + \delta\omega(x)$$

where

- u^μ is the four-velocity
- $\delta\omega(x)$ represents local modulation

The expectation value defines the physical normalization

$$\langle \partial_t \phi \rangle = \omega_c$$

Thus $\phi(x)$ describes fluctuations of proper-time phase evolution relative to inertial reference clocks.

3. Free Clock-Field Dynamics

In flat spacetime the minimal quadratic action is

$$S_\phi^{free} = \int d^4x \left(-\frac{1}{2} \partial_\mu \phi \partial^\mu \phi \right)$$

Variation yields the massless Klein–Gordon equation

$$\square \phi = 0$$

Quantization gives

$$\phi(x) = \int \frac{d^3k}{(2\pi)^3 2\omega_k} (a_k e^{-ik \cdot x} + a_k^\dagger e^{ik \cdot x}), \quad \omega_k = |\mathbf{k}|$$

The Feynman propagator is

$$\langle 0 | T\phi(x)\phi(y) | 0 \rangle = \int \frac{d^4k}{(2\pi)^4} \frac{i}{k^2 + i\epsilon} e^{-ik \cdot (x-y)}$$

The vacuum two-point function (Wightman function) is

$$\langle 0 | \phi(x)\phi(y) | 0 \rangle = \frac{1}{4\pi^2} \frac{1}{(x-y)^2 - i\epsilon(x^0 - y^0)}$$

This propagator preserves Lorentz invariance and exhibits the standard $1/(x-y)^2$ decay expected for massless scalar correlations.

4. Covariant Couplings to Electromagnetism and Curvature

To lowest derivative order the generally covariant effective action takes the form

$$S = \int d^4x \sqrt{-g} \left[\frac{c^4}{16\pi G} R - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \frac{1}{2} \nabla_\mu \phi \nabla^\mu \phi + \frac{\alpha}{\omega_c} \phi F_{\mu\nu} F^{\mu\nu} + \frac{\gamma}{\omega_c^2} \phi R + \frac{\delta}{\omega_c^2} \nabla_\mu \phi \nabla_\nu \phi G^{\mu\nu} \right]$$

Here α, γ, δ are dimensionless coefficients.

The Compton frequency enters as an effective matter-sector scale associated with internal phase evolution rather than a fundamental gravitational cutoff scale.

5. Field Equation for the Clock Field

Variation with respect to ϕ yields

$$\square \phi = -\frac{\gamma}{\omega_c^2} R - \frac{\delta}{\omega_c^2} \nabla_\mu (G^{\mu\nu} \nabla_\nu \phi) - \frac{\alpha}{\omega_c} F_{\mu\nu} F^{\mu\nu}$$

In flat spacetime without background fields this reduces to

$$\square \phi = 0$$

Thus curvature and electromagnetic invariants act as sources for clock-field fluctuations.

6. Long-Range Correlations in Squeezed Vacuum States

Quantum pair-creation processes naturally generate squeezed vacuum states. These arise in

- parametric down-conversion,
- Hawking radiation,
- cosmological particle production.

For a squeezing parameter r ,

$$|sqz\rangle = \exp\left(\frac{1}{2}(\zeta^* a_k a_{-k} - \zeta a_k^\dagger a_{-k}^\dagger)\right) |0\rangle$$

The two-point function becomes

$$\langle\phi(x)\phi(y)\rangle_{sqz} = \langle 0 | \phi(x)\phi(y) | 0 \rangle + \Delta(x, y)$$

Where the additional correlation $\Delta(x, y)$ is

$$\Delta(x, y) = \int \frac{d^3k}{(2\pi)^3 2\omega_k} \sinh^2 r \cos(\mathbf{k} \cdot (\mathbf{x} - \mathbf{y}))$$

For spectra dominated by long-wavelength squeezed modes,

$$\Delta(x, y) \approx \text{constant} \quad (|\mathbf{x} - \mathbf{y}| \ll \Lambda^{-1})$$

Thus spatially separated regions may share nearly identical clock-phase fluctuations.

7. Phase-Difference Correlation Between Spatially Separated Clocks

Define the phase-difference operator

$$\Delta_{AB} = \phi(t, \mathbf{X}_A) - \phi(t, \mathbf{X}_B)$$

Its variance is

$$\langle(\Delta_{AB})^2\rangle = 2(\langle\phi^2\rangle - \langle\phi(\mathbf{X}_A)\phi(\mathbf{X}_B)\rangle)$$

For infrared-dominated squeezed states,

$$\langle(\Delta_{AB})^2\rangle \rightarrow 0$$

Thus distant clocks may exhibit strongly correlated phase evolution.

Because

$$[\phi(x), \phi(y)] = 0 \text{ (spacelike separation),}$$

micro-causality remains preserved.

8. Acceleration-Dependent Phase Modulation

Within the Unified Equivalence Principle framework, acceleration relates to oscillator excitation number through

$$a = a_c \sqrt{\tilde{n} + \frac{1}{2}}, \quad a_c = \frac{mc^3}{\hbar}$$

Acceleration therefore modifies clock-phase evolution according to

$$\delta\phi \propto \frac{1}{c^2} \int a \, dt$$

Spatially separated accelerated systems acquire relative phase shifts that depend on their excitation structure.

This provides an experimentally testable modulation of clock-field correlations.

9. Cosmological Clock-Noise Background

Inflationary particle production generates relic squeezed vacuum states across cosmological scales. The largest correlated wavelength inherited from recombination horizon structure implies a characteristic angular frequency

$$\omega_r = \frac{c}{L_r}$$

Using

$$L_r \sim 3.6 \times 10^{22} \text{m}$$

Gives

$$\omega_r \approx 8.3 \times 10^{-15} \text{ rad/s}$$

This predicts a common-mode correlated phase-noise background potentially observable in

- global optical clock networks
- pulsar-timing arrays

including experiments such as NANOGrav.

10. Consistency with Relativistic Quantum Field Theory

The clock-field framework satisfies standard consistency requirements:

Requirement	Status
Lorentz covariance	manifest
micro-causality	preserved
energy positivity	standard scalar Hamiltonian
unitarity	squeezed states unitary
GR compatibility	covariant coupling structure

Standard quantum field theory is recovered in the limit $r \rightarrow 0$.

11. Conclusion

We constructed a covariant effective field theory in which Compton-phase evolution is represented by a propagating scalar clock field.

The theory predicts:

- curvature-induced clock-field sourcing
- electromagnetic coupling through invariant operators
- long-range correlations in squeezed vacuum states
- acceleration-dependent phase modulation
- relic cosmological clock-noise background

These results suggest that Compton-phase dynamics may represent a physically relevant sector of relativistic quantum theory linking proper-time evolution with long-range quantum correlations.

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